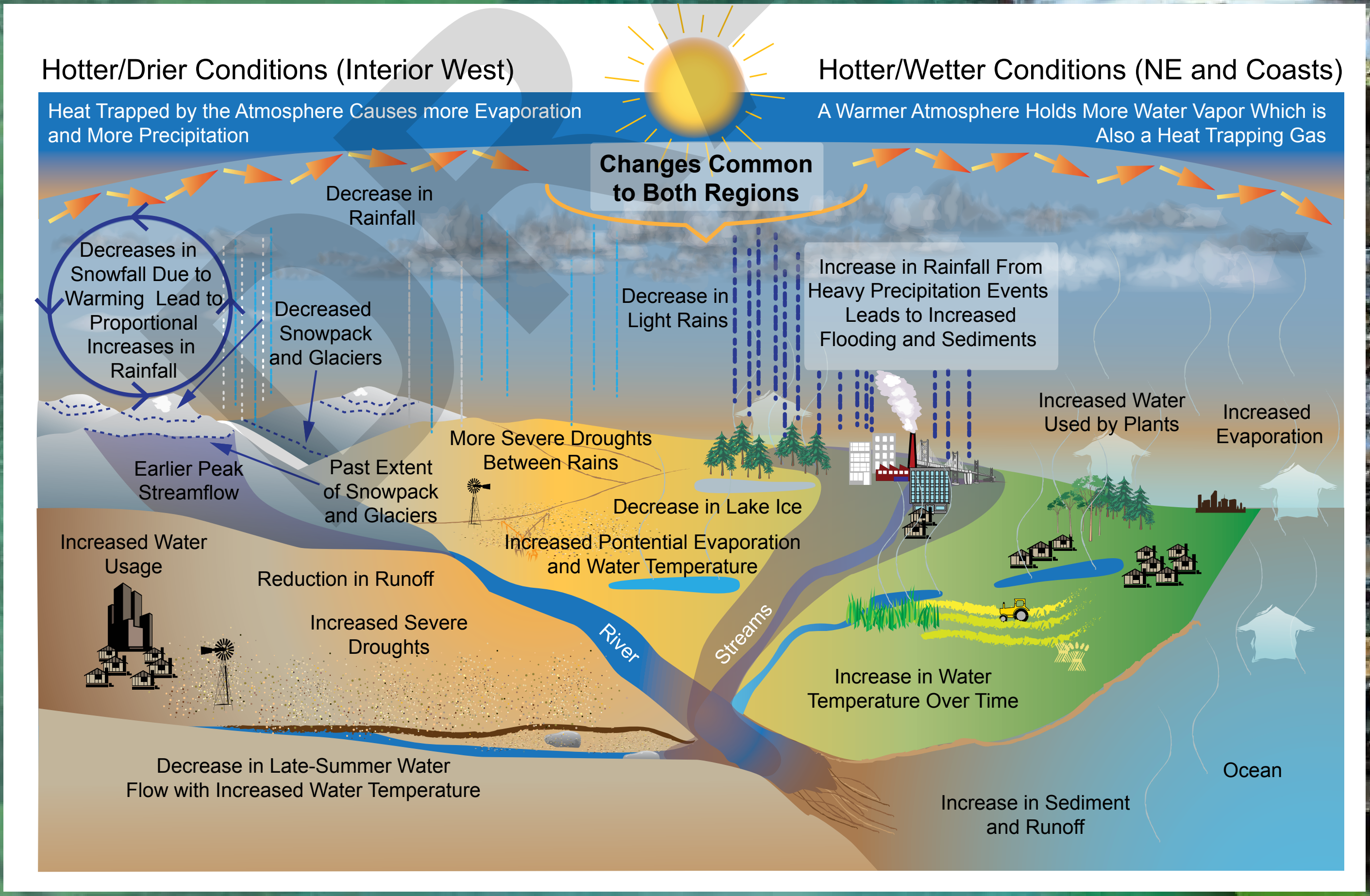
Water Resources

- Climate change will continue to alter the water cycle, affecting where, when, and how much water is available for human and ecosystem uses.
- The quality and quantity of surface water and groundwater are affected by a changing climate.
- Climate change will add yet another burden to already stressed water systems.
- The past century is no longer a reasonable guide to the future for water management.

Nothing is more essential to life and more sensitive to climate change than water. Human society, plants, animals, and ecosystems are all sensitive to variations in the quality, quantity, and timing of water, including precipitation, runoff, and evaporation, as well as the storage of water in glaciers, snow, soil, groundwater, lakes, wetlands, and reservoirs. All of these, in turn, are sensitive to climate change[1].

While climate change affects water, water use also affects climate. A great deal of energy is used to pump, pressurize, treat, transport, and heat water. In planning for the future, it would thus be wise to consider how water supplies will be affected by climate change as well as how water supply choices will influence energy use and therefore climate. For example, one of the options for providing more fresh water is desalination, but this is a very energy intensive process. If energy-intensive water supply options are pursued, it will be important to consider the impact of the chosen energy sources on global climate change.



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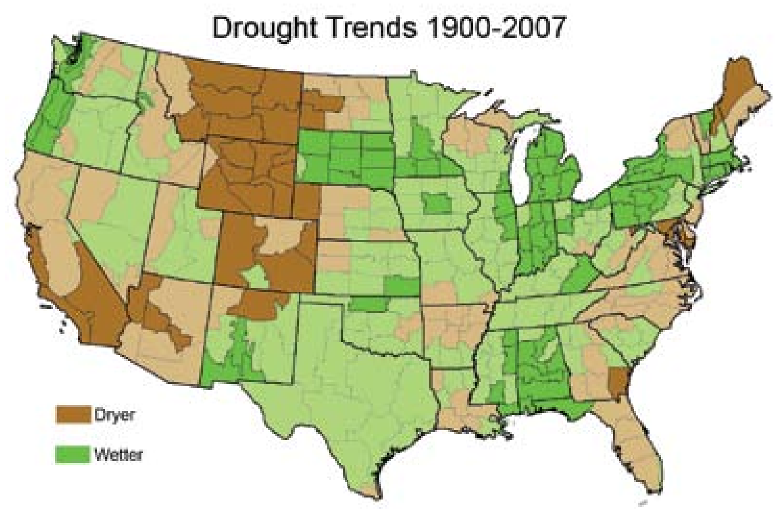
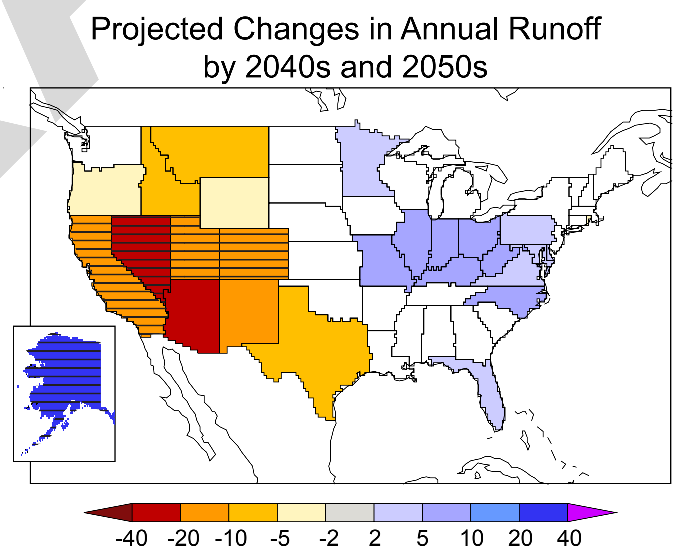


Climate divisions with statistically significant trends are highlighted[22].

Changes in Timing, Amounts, Types, and Distribution of Precipitation

Substantial changes to the water cycle are expected as the planet warms because water is one of the primary mechanisms used by the Earth for redistributing heat. Evidence is mounting that human-induced climate change is altering many of the existing patterns of precipitation in the United States, including when, where, how much, and what kind of precipitation falls. A warmer climate increases evaporation of water from land and sea, and allows the atmosphere to hold more moisture. For every 1°F rise in global temperature, the water holding capacity of the atmosphere increases by about 4 percent[2]. Coupled with other warming-related changes, this tends to lead to longer and more severe droughts in some areas, especially in arid and semi-arid areas like the Southwest. The additional atmospheric moisture also results in more overall precipitation in some areas, especially in the Northeast and Alaska. Over the past century, precipitation and streamflow have increased in the East and Midwest, with a reduction in drought duration and severity. The West has had reductions in precipitation and increases in drought severity and duration, especially in the Southwest. In most areas of the country, the proportion of rain versus snow has changed to more rain and less snow regardless of changes in overall precipitation during the last 50 years. Despite this general shift from snow to rain, lake effect snowfalls have increased where reduced ice cover leaves open water for evaporation and temperatures are still cold enough to produce heavy snow events. Heavy snowfall has increased in many northern parts of the United States, in contrast to the south where conditions are often too warm and less heavy snow has been observed[4].

While it sounds counterintuitive, a warmer world produces both wetter and drier conditions because even though overall precipitation will increase, the distribution of precipitation will change. More precipitation comes in heavy downpours (which can causing flooding) rather than light events. In the past century, averaged over the U.S., total precipitation has increased by about 7 percent, while the heaviest 1 percent of rain events increased by nearly 20 percent. In addition, observations also show that over the past several decades extended dry periods are becoming more frequent in the eastern and southwestern U.S.[5]. Longer periods between rainfalls, combined with higher air temperatures, dry out soils and vegetation, causing drought.



Percentage change relative to 1900-1970 baseline. Any color indicates that greater than 66 percent of models agree on the direction of change, *i.e.*, that it is an increase or a decrease; hatching indicates that greater than 90 percent of models agree on this[5a].

Changes in Future Runoff Amounts

Runoff, which accumulates as stream flow, is the amount of precipitation that is not evaporated, stored as snowpack or soil moisture, or filtered

Highlights of Impacts by Sector

Sector	Impacts
Human Health	Heavy downpours increase incidence of water-borne diseases and floods resulting in hazards to human life and health.
Energy Production and Use	Reductions in hydropower. Reduced power generation in fossil fuel and nuclear plants due to increased water temperatures and reduced cooling water availability.
Transportation	Floods disrupt transportation. Heavy downpours adversely affect surface and air transportation. Declining Great Lakes levels reduce freight capacity.
Agriculture and Land Resources	Heavy downpours increase soil erosion and can reduce crop yields. Earlier spring snowmelt leads to increased number of fires.
Natural Environment and Biodiversity	Cold water fish threatened by rising water temperatures.

down to groundwater. The proportion of precipitation that runs off is determined by a variety of factors including temperature, windspeed, humidity, sun intensity, vegetation, and soil moisture. Increases and decreases in precipitation do not necessarily lead to equal increases and decreases in runoff. For example, droughts cause soil moisture reductions that can reduce expected runoff until soil moisture is replenished. Thus, water-saturated soils can generate floods with only moderate additional precipitation. Climate models consistently project that the East will experience increased runoff, and moving westward, there will be substantial declines in the Interior West, especially the Southwest. Projections for runoff in California and other parts of the West also show reductions, although less than in the Interior West.

Changes in Snowmelt Dominated Systems

Large portions of the West rely on snowpack as a natural reservoir to hold winter precipitation until it later runs off as streamflow in spring, summer, and fall. Over the last 50 years, there have been widespread temperature-related reductions in snowpack in the West, with the largest reductions occurring in lower elevation mountains in the Pacific Northwest and California where snowfall occurs at temperatures close to the freezing point. Runoff is occurring earlier in the year in snowmelt-dominated areas of the West, in some cases, up to 20 days earlier. Future projections for most snowmelt-dominated basins in the West consistently indicate earlier spring runoff, which produces lower late-summer streamflows[6].

Observed Changes in Water Resources During the Last Century[7]

Event	Increase/ Decrease	Region
1 to 4 Week Earlier Peak Streamflow due to earlier warming-driven snowmelt		West and Northeast
Proportion of Precipitation falling as snow	↓	West
Duration and extent of snow cover	↓	Most of U.S.
Mountain Snow Water Equivalent	↓	West
Annual Precipitation	↑	Most of U.S.
Annual Precipitation	↓	Southwest
Frequency of Heavy Precipitation Events	↑	Most of U.S.
Streamflow	↑	Most of East
Glacier Size or Extent	↓	U.S. Western Mountains, Alaska
Water Temperature of Lakes	↑	Most of U.S.
Ice Cover	↓	Great Lakes
Time between rainfall events	↑	Most of U.S.
Periods of Drought	↑	West, Southeast
Salination of Surface Waters	↑	Florida, Louisiana
Widespread Thawing of Permafrost	↑	Alaska

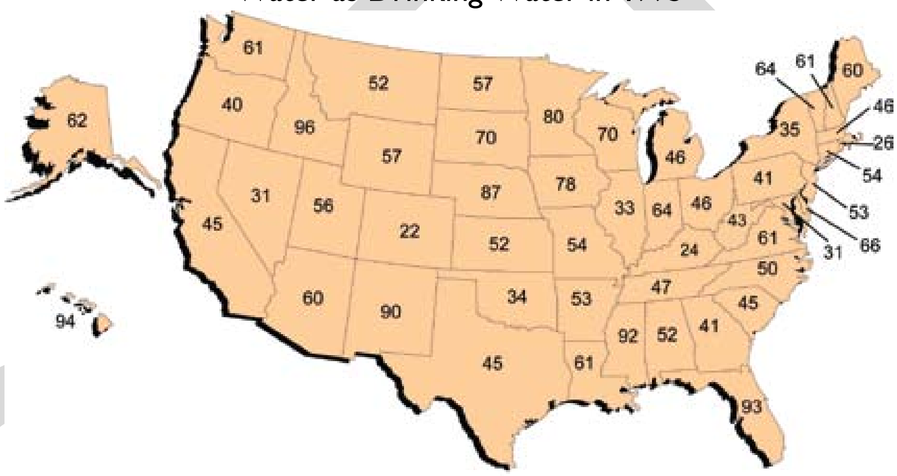
The quality and quantity of surface water and groundwater are affected by a changing climate.

Changes in water quality

Increased air temperatures lead to higher water temperatures, which have already been detected in many streams, especially during low flow periods. In lakes and reservoirs, higher water temperatures lead to longer periods of stratification (when surface and bottom waters don't mix). Dissolved oxygen is reduced in lakes, reservoirs, and rivers at higher temperatures. Oxygen is an essential resource for many living things, and its availability is reduced at higher temperatures both because the amount that can be dissolved in water is lower and because respiration rates of living things are higher. Low oxygen stresses aquatic animals such as cold-water fishe and the insects and crustaceans on which they feed.

Many forms of water pollution including sediments, nitrogen from agriculture, disease pathogens, pesticides, herbicides, salt, and thermal pollution will be made worse by observed and projected increases in precipitation intensity and longer periods when streamflow is low. However, regions that experience increased streamflow will have the benefit of pollution being more diluted. Heavy downpours lead to increased sediment in runoff and outbreaks of water-borne diseases[8]. Increases in pollution carried to lakes, estuaries, and the coastal ocean, especially when coupled with increased temperature, can result in blooms of harmful algae and bacteria.

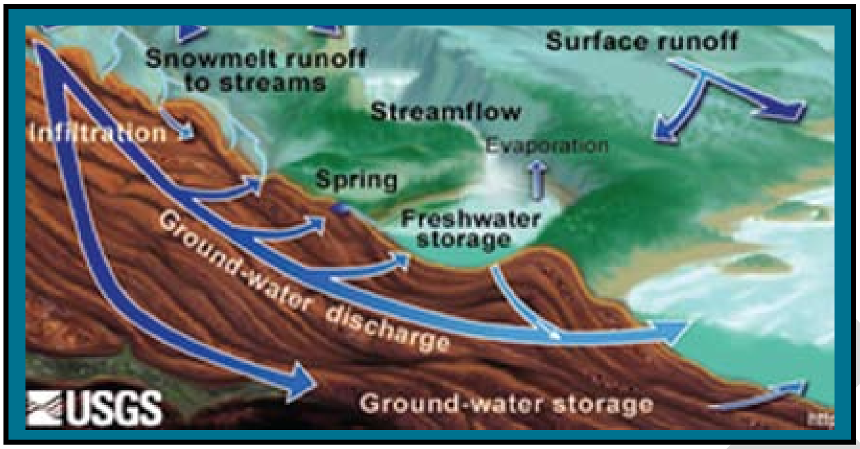
Percent of State Population Using Ground Water as Drinking Water in 1995



Changes in Groundwater

Many parts of the U.S. are heavily dependent on groundwater for drinking and residential water supplies. How climate change will affect groundwater is not well known, but increased water demands by society in regions that already rely on groundwater will clearly stress this resource, which is often drawn down faster than it can be recharged. Changes in the water cycle that reduce precipitation or increase evaporation and runoff would reduce the amount of water available for recharge. Changes in vegetation and soils that occur as temperature changes or due to fire or pest outbreaks are also likely to affect recharge by altering evaporation and infiltration rates. Increased frequency and magnitude of floods are likely to increase groundwater recharge in semi-arid and arid areas where most recharge occurs through dry streambeds after heavy rainfalls and floods.

Sea-level rise is expected to increase saltwater intrusion into coastal freshwater aquifers, making them unusable without desalination. Increased evaporation or reduced recharge into coastal aquifers will exacerbate saltwater intrusion. Shallow groundwater aquifers that exchange water with streams are likely to be the most sensitive part of the groundwater system to climate change[9]. Small reductions in groundwater levels can lead to large reductions in streamflow and increases in groundwater levels can increase streamflow[10]. Further, the interface between streams and groundwater is an important site for pollution removal by micro-organisms. Their activity will change in response to increased temperature and increased or decreased streamflow as climate changes, and this will affect water quality.



Place holder for illustration of ground water, surface water connections

The role of wetlands, streams, and interface zones in water purification

Streams, wetlands, and ecosystems in the riparian zone (bordering rivers and surrounding lakes) play an important role in maintaining water quality, particularly because they remove nitrogen from surface water and groundwater flowing through them[11]. Farmers apply nitrogen fertilizer to enhance crop growth but current agricultural practices tend to deposit more nitrogen than necessary[12]. When it runs off to streams and rivers, and ultimately coastal zones, it can cause blooms of harmful algae and low oxygen conditions[13]. Streams along the way remove nitrogen[14], and riparian zones and the interface between streams and groundwater are particularly active sites of nitrogen removal[15,16]. Streams become much less efficient at removing nitrogen when overloaded[17], and riparian zones and the interface between streams and groundwater lose their capacity to remove nitrogen if they become disconnected from the stream, as is likely to happen under reduced streamflow or increased groundwater withdrawals[18]. Although nitrogen is the best-studied, other pollutants, such as phosphorus and pesticides, will also cause impacts in response to projected changes in climate and the water cycle.

Climate change will add yet another burden to already stressed water systems.

In many places, the nation's water systems are already taxed due to aging infrastructure, population increases, and conflicts between water for recreation, farming, hydropower, and ecosystems. Climate change will add another factor to many existing water management challenges.

Rapid Regional Population Growth

The U.S. population is estimated to have grown by almost 7 percent since the 2000 census to over 300 million. Current Census Bureau projections are for this growth rate to continue, with the national population projected to reach 350 million by 2025 and 419 million by 2050. The highest rates of population growth to 2025 are projected to occur in areas that are at risk for reductions in water supplies due to climate change, such as the Southwest.

Eroded concrete water pipe

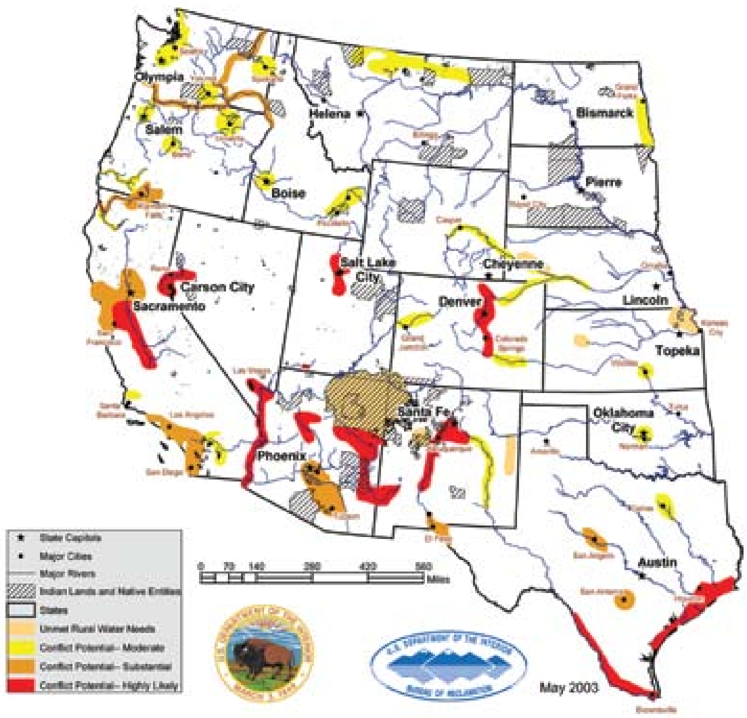
Aging Water Infrastructure

The nation's drinking water and wastewater infrastructure is aging. In older cities, buried water mains can be over 100 years old and breaks of these lines are a significant problem. Sewer overflows resulting in the discharge of untreated wastewater also occur frequently. The Environmental Protection Agency has identified a potential funding shortfall for drinking water and wastewater infrastructure of over $500 billion by 2020. Heavy downpours will exacerbate existing problems in many cities, especially where stormwater catchments and sewers are combined. Drinking water and sewer infrastructure is very expensive to install and maintain. Climate change will present a new set of challenges for designing upgrades to the nation's water delivery and sewage removal infrastructure[19].

Existing Water Disputes throughout the Country

Many locations in the U.S. are already undergoing water stress. The Great Lakes states are working on an interstate compact to protect against reductions in lake levels and potential water exports. Georgia, Alabama, and Florida are in a dispute over water for drinking, recreation, farming, environmental purposes, and hydropower in the Apalachicola-Chattahoochee-Flint system. The State Water Project in California is facing a variety of problems in the Sacramento Delta including endangered species, saltwater intrusion, and potential loss of islands due to flood- or earthquake-caused levee failures. A dispute over endangered fish in the Rio Grande has been ongoing for many years. The Klamath River in Oregon and California has been the location of a multi-year disagreement over native fish, hydropower, and farming. The Colorado River has been the site of numerous interstate quarrels over the last century. By changing the existing patterns of precipitation and runoff, climate change will add another stress to existing problems.

Potential Water Supply Crises by 2025



Areas where existing supplies are not adequate to meet water demands for people, agriculture and the environment.

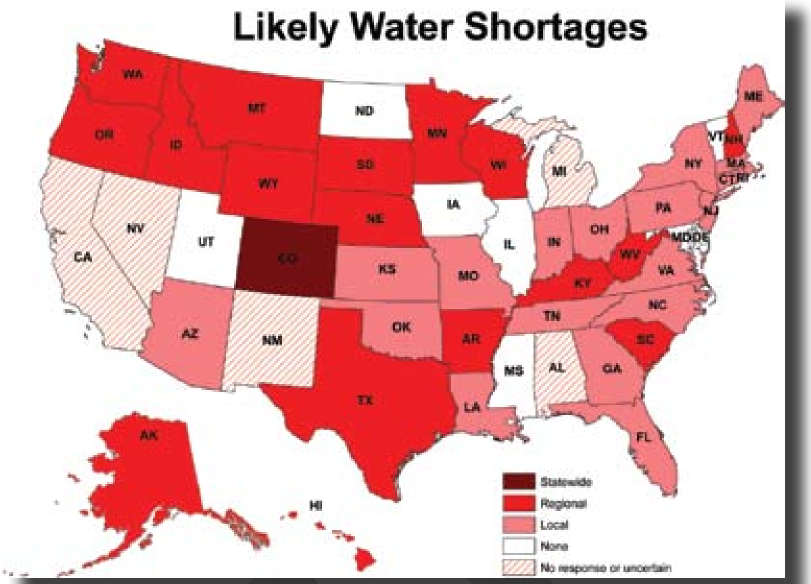
Spotlight on the Colorado River

The Colorado River system supplies water to over 30 million people in the Southwest including Los Angeles, Phoenix, Las Vegas, and Denver. Reservoirs in the system, including the giant lakes Mead and Powell, were nearly full in 1999 with almost four times the annual flow of the river stored. By 2007, the system had lost approximately half of that storage after enduring the worst drought in 100 years of record keeping. Runoff was reduced due to low winter precipitation, and warm, dry, and windy springs that substantially reduced snowpack.

Numerous studies over the last 30 years have indicated that the river is likely to experience reductions in runoff due to climate change. In addition, diversions from the river to meet the needs of cities and agriculture are now nearly equal to its average flow. Under current conditions, even without climate change, large year-to-year fluctuations in reservoir storage are possible. If reductions in flow projected to accompany global climate change occur, water managers will be challenged to satisfy all existing demands, let alone the increasing demands of a rapidly growing population[20].

Declines in Lake Powell from June 2002 to December 2003 during a severe drought.

The past century is no longer a reasonable guide to the future for water management.



In 2002 and 2003, the Government Accountability Office conducted a survey of water managers in the 50 states and received responses from 47 states; California, Michigan, and New Mexico did not participate. One of the questions asked of water managers: in the next 1-10 years which, if any, portions of their states are likely to experience water shortages under average water conditions. Managers were instructed to use the last 10-20 years to determine average water conditions, and drought was defined as a deficiency of precipitation, including snow, over several consecutive years[21].

Water planning has historically been based on the idea that supply and demand would fluctuate within an unchanging envelope of climate variability established by stream gauges and other data collected during the century. Reservoir flood operations, reservoir yields, urban stormwater runoff, and projected water demands are based on these data. Because climate change will significantly modify many aspects of the water cycle, the assumption of an unchanging climate is no longer appropriate for many aspects of water planning. Past assumptions about supply and demand will need to be revisited for existing water projects as well as for proposed projects. New methods for incorporating climate change impacts and the resulting additional uncertainty have been well developed in academic case studies over the past decade or so, but acceptance and use of these experimental methods by water management professionals has, until very recently, been slow to develop.

Water systems are now under multiple stresses including a changing climate, population growth, environmental limitations, and competition for limited supplies by agriculture, hydropower, recreation, and municipalities. The intersection of substantial changes in the water cycle along with multiple stresses means that water planning will be doubly challenging. At the same time, many potential adaptations are limited by institutional constraints. Total U.S. water diversions peaked in the 1980s, which implies that expanding supplies to meet new needs will not be a viable option, especially in arid areas likely to experience less precipitation.

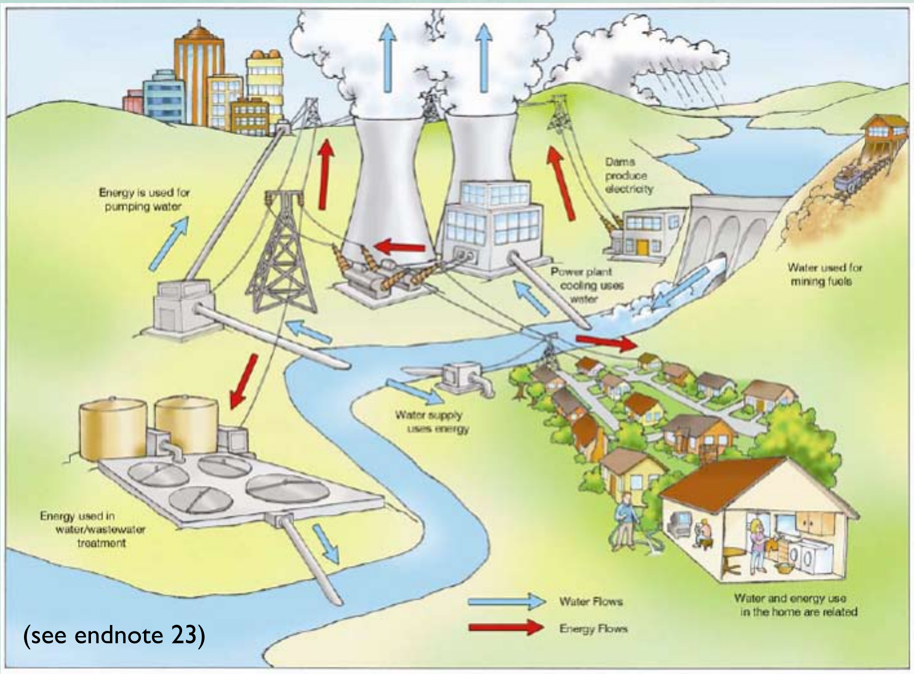
Water management has reduced the impacts of significant natural climate variability. The ability to modify operational rules and water allocations is likely to be critical for the protection of infrastructure, for public safety, to ensure reliability of water delivery, and to protect the environment. There are, however, many institutional and legal barriers to such changes in both the short and long term. Four examples:

- The allocation of the water in many interstate rivers is governed by compacts, court decrees, and other agreements that are difficult to modify.
- Reservoir operations are governed by "rule curves" that require a certain amount of space to be saved in a reservoir at certain times of year to capture a potential flood. Developed by the Army Corps of Engineers based on historic flood data, many of these rule curves have never been modified, and modifications may require Environmental Impact Statements.
- In most parts of the West, water is allocated based on a "first in time means first in right" system, and because agriculture was developed before cities were established, large volumes of water typically are allocated to agriculture. Transferring these rights, even for short periods, can involve substantial expense and time and can be socially divisive.
- Changes in forecasting systems and methods are likely to be required to support water management agencies in adapting to climate change, but these processes are not controlled at an institutional level by the water management agencies themselves. High level leadership is required to integrate these activities.

Water and Energy

Water and energy are interconnected. Both are expected to be under increasing pressure in the future and both will be affected by a changing climate. Water is used directly for hydropower, and cooling water is critical for nearly all other forms of electrical power generation (see Energy). Large amounts of energy are needed for pumping, pressurizing, heating, and treating drinking and wastewater. As a result, conserving water has the dual benefit of conserving energy, and potentially reducing greenhouse gas emissions if fossil fuels are the predominant source of that energy. Water managers will increasingly need to consider the energy and related greenhouse gas emission impacts of proposed new water projects.

Water and Energy Connections



(see endnote 23)

Another nexus between water and energy is that planting vegetation can significantly reduce air conditioning costs. However, there is an important trade-off. Places where energy use for cooling is already a substantial cost are often those with water-supply problems. In addition, planting vegetation increases water loss to the atmosphere by plants, thus reducing run-off to streams[21].

Adaptation Strategies

Different areas of the country will face different adaptation challenges. As a result, adaptations will be regionally specific. For example, some areas will need additional storage while others already have substantial storage; some areas will experience predominately wetter conditions with more runoff and floods, while other areas face increases in drought length and severity. No single universal adaptation strategy will work everywhere.

Supply-side adaptations to climate change will involve many traditional techniques including building new surface reservoirs, transferring water from agriculture or other uses, transferring water among basins, and removal of high water-use vegetation, although some of these options carry high environmental and economic costs. Storing water in underground aquifers and desalinizing seawater are considered by some to be useful new techniques, although both involve substantial energy for pumping and treatment. Supply side options may have considerable problems. For example, new reservoirs will have to overcome environmental problems, a lack of good sites, and large expense; water transfers are frequently contentious. Most supply side options involve large capital costs and large new increments of water.

Demand side adaptations for agricultural water use include improved water efficiency measures such as increased reliance on drip irrigation and gray water use. General demand side adaptations include voluntary and mandatory water conservation, various pricing measures (which would require increased installation/use of metering), and the further development of water markets in which water is bought and sold like any commodity and thus shifted to uses that have the highest monetary value. Demand side options are generally less costly, but involve changes in human behavior with unknown results.